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Shoreline management plan for embayed beaches: A case study at Vengurla, west coast of India

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ABSTRACT

Embayed beaches play an important role in ensuring the environmental and morphological sustenance of coastal areas. Coastal processes along embayed beaches are different from that of open beaches. Shoreline management along embayed beaches is a major concern for engineers and policy makers worldwide, which requires a clear understanding of shoreline evolution. As shoreline evolution is the combined effect of natural and human activities, which vary over space and time, numerical models are vital to understanding shoreline change behaviour. The present study was carried out at Vengurla, an embayed beach along the west coast of India, using a well established numerical model. Wave climate, bathymetry, sediment characteristics and initial coastline were the primary inputs for the model. Nearshore wave climate at a depth of 15 m was collected using a wave rider buoy for the year 2015. Bathymetry and nearshore sediments were also collected during the same year. The initial coastline was extracted from satellite imagery of the year 2015. Shoreline change was studied over the preceding 26 years (1990–2016) using nine different satellite images. The model was then run for the following 26 years (2015–40), with present wave climate and future expected increase in wave heights. The results indicate that Vengurla embayed beach is not only affected by various anthropogenic modifications including the destruction of sand dunes, but also by future climate-change projections. We propose the implementation of a dune based shoreline management plan with strict regulations and awareness program. The findings of this study will interest policy makers and environmental managers, guiding them in developing management strategies for protection of this embayed beach. Overall, this paper demonstrates how numerical modelling can help in designing the shoreline management plan for an embayed beach, which can lead to save costs and to prevent further destruction of the beach.

1. Introduction

Coastal zones have been the centre of social and economic development since millennia. In fact, especially in the developing regions, coastal tourism is an important economic activity (Division for Sustainable Development, 2015; UNEP, 2009). To ensure that the coastal system continues to provide goods and services to future generations, there is a need to ensure the conservation and sustainable management of this vital ecosystem (Shailesh Nayak, 2017). Of the roughly 356,000 km of coastline over the globe (Central Intelligence Agency, 2016), 51% represent an embayed beach morphology (Short and Masselink, 1999). Embayed beach, also known as headland bay beach, is a term referring to a sandy shoreline bounded by headlands or rock outcrops, where the shoreline assumes some form of curvature (Short and Masselink, 1999; Klein and Menezes, 2001). Embayed beaches often develop an asymmetric form that is characterised by a shadow zone with strong curvature adjacent to the downdrift headland, a gently curved transition zone, and a straight end, which is normal to the angle of incidence of the more energetic waves (Klein et al., 2002). Although embayed beach morphology represents about 51% of the world coastline, due to the complexity of headland on the morphodynamic behaviour, it has received less attention compared to unconstrained sandy beach (Short and Masselink, 1999; Klein et al., 2002). Thomas et al. (2016) developed a model for an embayed beach in West Wales that can predict future shoreline positions aligned with shoreline management plan epochs. Further, the model is capable of informing shoreline assessments at local, regional and international scales. It does so by identifying locations of vulnerability which can help develop management strategies to improve resilience under sea level rise and climate change scenarios. For coastal zone managers, it is imperative to understand the morphological variability of these embayed beaches (Thomas et al., 2015).

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The National Centre for Coastal Research (NCCR) initiated shoreline management studies in India (formerly, Integrated Coastal and Marine Area Management Project Directorate, ICMAM PD), who prepared management plans for various sites along the Indian coast (www.nccr.gov.in; ICMAM, 2006; Subramanian et al., 2007a,b; Thomas et al., 2007, 2013). Shoreline management plans have also been proposed for selected beaches along Maharashtra coast (Black et al., 2017a). The study also identified significant knowledge gaps in understanding the coastal process along the Maharashtra coast and recommended numerical modelling before taking final management decisions. To the best of our knowledge, there are no detailed studies including numerical modelling carried out to understand the coastal processes for suggesting management plans of the embayed beaches in India. In recent times, the integration of numerical models with remote sensing data have received considerable attention in understanding and predicting shoreline evolution. Remote sensing data were used as reference data for analyzing short-term and long-term shoreline changes (Pradjoko and Tanaka, 2010; Ford, 2013). Satellite imageries provide an instantaneous shoreline position to calculate the rate of change. As a result, satellite imageries are becoming a reliable and practical method to delineate the shoreline positions at spatio-temporal scales (Almonacid-Caballer et al., 2016; Li and Gong, 2016; Shailesh Nayak, 2017). However, due to their dynamic nature, the shoreline positions can fluctuate by a few meters across the beach on a daily basis (Romine et al., 2009).

This study focuses on the Vengurla embayed beach in Sindhudurg district, south Maharashtra, as it has significant socio-economic importance. The embayed beaches of Sindhudurg are the best and the most visited tourist destinations in Maharashtra. Beaches of the Maharashtra coast are small, crescent shaped and flanked by promontories. Many headland bounded beaches in Maharashtra are log spiral and parabolic in shape (Karlekar, 2015). Vengurla coast mainly consists of two headlands on either side of the coast, forming an embayed beach. These headlands, which are made up of granites and gneissic rocks have high resistance against the waves. Some of the geomorphic features along the study area are sandy beach, sand dunes, headlands, rocky shore, coastal plain, tidal flats and plateau (Fig. 1). A stabilized sand dune is present parallel to the coast, and covered with casuarina plantation. A small inlet is present at the northern side of the coast, where the waves intrude during high tide time. Mangroves were seen on both sides of the inlets. A well developed sandy beach was seen all along the coast with an average width of 40–50 m. Further, most embayed beaches along the Maharashtra coast are backed by cliffs or embankments. Thus, landward displacement in case of sea-level rise is not possible, which raises a major concern for the evolution of such beaches. Therefore, changes in the embayed beaches due to natural or artificial reasons could be detrimental to the region's economy.

Given the importance of the embayed beaches to the economics of the region, the present study was carried out. This paper investigates the ability of numerical models to predict the morpho-dynamics of Vengurla embayed beach. Using the remote sensing data (1990–2016), recent morphological observations (2015–16) from Vengurla beach, and integrating remote sensing and numerical models, the shoreline evolution was investigated in order to suggest management plans. Also, the shoreline changes were predicted for the upcoming 26 years, along with climate change scenarios.

2. Regional settings

Vengurla embayed beach stretches over 5 Km length between two headlands (Fig. 2). Seawalls of about 0.8 Km length are present in the southern sector and a paved path of about 0.7 Km is constructed along the northern part. The annual average significant wave height (H_s) was ~ 1 m and the highest H_s was ~2 m during the monsoon period (Amrutha et al., 2015). The tides are predominantly mixed semi-diurnal and the tidal range was 1.3 m during the neap tide and 2.3 m during the

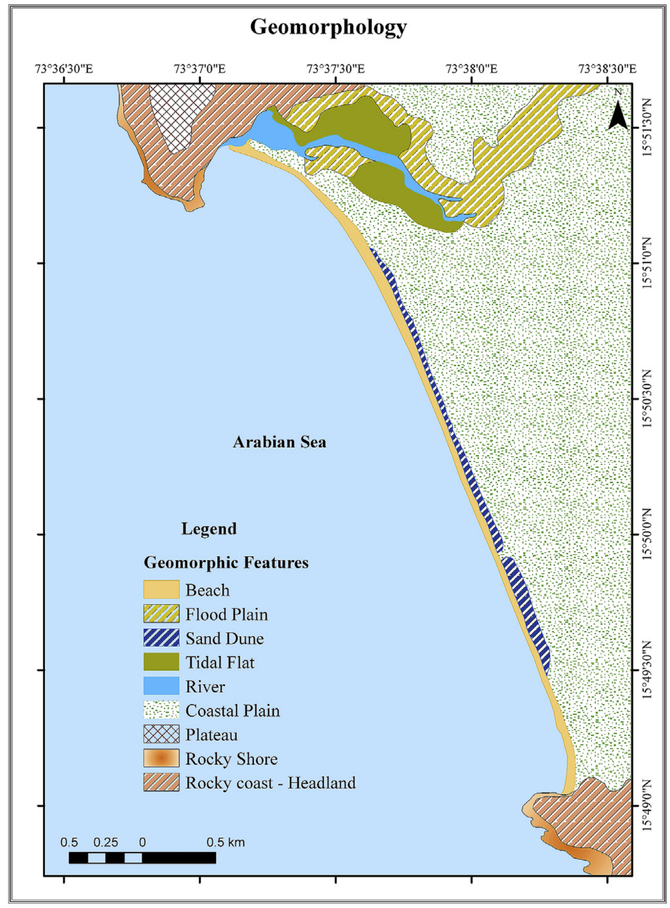

Fig. 1. Geomorphology along Vengurla coast.

spring tide. The annual net Longshore Sediment Transport Rate (LSTR) along Vengurla coast was in the range of -7778 to $-9015\,m^3$ with an average of $-8511\,m^3$ towards south (Noujas et al., 2018). The gross LSTR was $1.18 \times 10^5\,m^3$/year. Based on the grain size analysis, the backshore indicates a depositional setting whereas the bermline and foreshore are characterised by erosion (Sathish et al., 2018).

Vengurla coast is subjected to seasonal erosion due to the storm wave during the monsoon period. The sand dunes present throughout the backshore form partial protection to the beach (Fig. 1). However, the dunes have been damaged at many locations, due to various commercial and local needs. In order to protect the houses in the southern side of the study area during the monsoon season, a seawall of 0.8 km was constructed (Fig. 2). In addition, a paved path was constructed in the northern part of the study region, in order to both protect the houses and provide recreational use (Fig. 2). The construction of both the seawall and the paved path damaged the existing sand dunes. These hard structures also create end erosion, causing further destruction of the sand dunes in some areas.

3. Materials & methods

3.1. Data collection

Waves were collected at a depth of 15 m (15.83265° N, 73.5681° E) from January to December 2015 using wave rider buoy. The vertical and horizontal (eastward and northward) displacement data were obtained from the respective accelerations measured by the buoy. The data processed every 30 min considered as one record and frequency of data collection was 1.28 Hz. Bathymetry, nearshore sediments and shoreline tracking were also collected during the same year. Shoreline

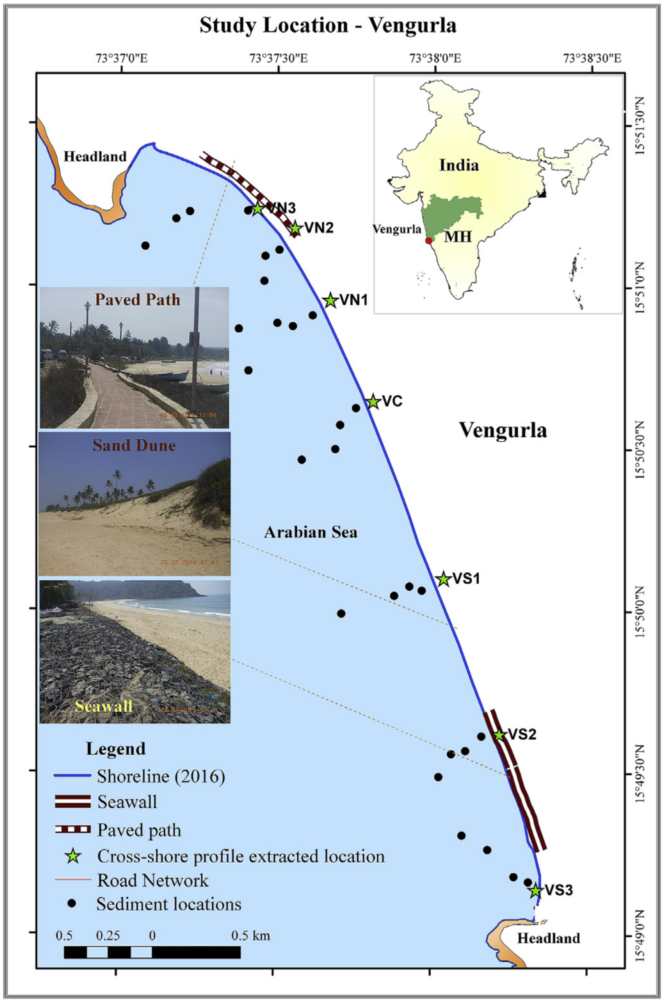

Fig. 2. Study location- Vengurla (South Maharashtra coast).

tracking was collected using Global Position System (GPS) in Real time Kinematics. Coastal current at Vengurla was collected in February–March 2015, using a Recording Current Meter (RCM) that was deployed along with a Tide Gauge. The RCM was equipped with a speed sensor Doppler current sensor 3820 with speed range of 0–300 cm/s at an accuracy of ± 0.15 cm/s. The in-built magnetic compass measures the direction for all angles with an accuracy of ± 5°. Tide Gauge is a type of MIDAS DWR and is fitted with high accuracy piezo-resistive pressure sensors with a range of 100 dB with accuracy of ± 0.01%.

The cross-shore profiles extracted from seven locations represent the actual geo-morphological condition during modelling (Fig. 3). The bathymetry for the nearshore was generated from surveyed bathymetric data using an echo-sounder up to ~12 m depth at a closed interval of 250 m transect during February 2015, and the same bathymetry was used for computing LSTR along the same sector (Noujas et al., 2018). Sediment data was collected along all the seven transects, from beach to offshore. The offshore depths are 1.5 m, 3 m, 5 m and 8 m (Fig. 2). The sediments were analysed for texture and subjected to statistical analysis (Blott and Pye, 2001; Folk and Ward, 1957). The median grain diameter d_{50} was considered as grain diameter for shoreline evolution computation.

3.2. Satellite data

Optical images such as Landsat (TM), Landsat (ETM+), IRS-P5 (PAN) and IRS-P6 (LISS-III and LISS-IV) of different acquisition dates were used as a primary data source to analyse the shoreline change rate for the past 26 years (Table 1). Initially, all the satellite imageries are rectified using field collected Ground Control Points (GCPs) in ERDAS IMAGINE 2013 software and brought into same projection system (Projection: UTM, Datum: WGS-84). Some of the uncertainties identified in satellite imageries are spatial resolution error, rectification error, seasonal variation, pixel variation and tidal variation. Since errors can impact the accuracy of extracted shoreline, it was given as input parameter in the shoreline file for analysing the change rate.

The wet-dry line was clearly visible from the satellite imageries and hence used as shoreline proxy (Kankara et al., 2014; Selvan et al., 2016). All the shoreline positions were extracted manually by visual interpretation technique (Elizabeth and Ian, 2005). Shoreline change analysis was carried out using Digital Shoreline Analysis System (DSAS, Version 4.3) in the ArcGIS 10.3 version (Thieler et al., 2009). Two different statistical methods in DSAS were adapted to calculate the shoreline change rate. For long-term shoreline analysis, Weighted Linear Regression rate (WLR) method was used, while the Net Shoreline Movement (NSM) method was used to study the yearly change. Long-term shoreline change rates were calculated by taking the slope of the regression line for all transects along the coast. Furthermore, in the WLR method, a weightage value was attached to shoreline data before analysing the change rate (Selvan et al., 2014).

The weight (w) is defined as a function of the variance in the uncertainty of the measurement (e):

$$w = \frac{1}{e^2}$$

Where, e = shoreline uncertainty value.

The shoreline positions extracted from satellite imageries were compiled in ArcGIS with five different attribute fields (Object ID, a unique number assigned to each transect, shape, shape length, ID, surveyed year and uncertainty values). An imaginary baseline was drawn parallel to the land ward shoreline position. Transect generated from the baseline intersects the shoreline position perpendicularly to calculate the shoreline change rate (Leatherman and Clow, 1983). A distance of 20 m was maintained between each transect throughout the coast. A total of 254 transects were generated with transects starting from the extreme south and continued towards the north of the study region.

3.3. Numerical modelling

Shoreline evolution were estimated using the LITPACK model developed by Danish Hydraulic Institute, Denmark (DHI, 2014). LITDRIFT (littoral drift) and LITLINE (shoreline evolution) are the main modules of LITPACK. LITLINE calculates the shoreline position based on the input of the wave climate as a time series. The model is based on one-line theory in which the cross-shore profile is assumed to remain unchanged during model run. Thus, the coastal morphology is solely described by the shoreline position (cross-shore direction) and the coastal profile at a given longshore position. The associated program LINTABL calculates and tabulates transport rates as functions of the water level, the surface slope due to regional currents, wave period, height and direction with respect to the shoreline normal. LITLINE calculates the shoreline evolution by solving a continuity equation for the sediment in the littoral zone. The governing sand conservation equation is given by

$$\frac{\partial y_c(x)}{\partial t} = -\frac{1}{h_{act}(X)}\frac{\partial Q(x)}{\partial x} + \frac{Q_{sou}(X)}{h_{act}(X)\Delta x}$$

Where, $y_c(x)$ = distance from the baseline to the coastline; t = time; $h_{act}(X)$= height of active cross-shore profile; $Q(x)$ = longshore transport of sediment expressed in volumes; x = longshore position; Δx = Longshore discretization step; $Q_{sou}(X)$= source/sink term expressed in volume.

$h_{act}(X)$ and $Q_{sou}(X)$ are calculated based on user specifications,

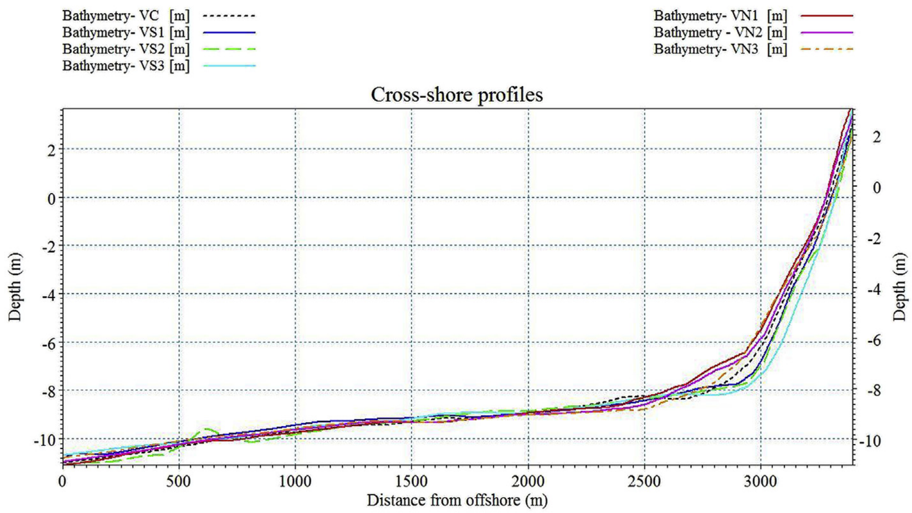

Fig. 3. Cross-shore profiles used for modelling.

Table 1
Details of satellite data sets used in the study.

Satellite Image	Sensors	Pixel Size(m)	Date	Source
Landsat 5	TM	30	1990	USGS
Landsat 7	ETM+	30	2000	USGS
IRS P5 (Cartosat-1)	PAN	2.5	2006	NRSC
IRS P6 (Resourcesat-1)	LISS-III	23.5	2008	NRSC
Resourcesat 2	LISS-IV	5.8	2012	NRSC
Resourcesat 2	LISS-IV	5.8	2013	NRSC
Resourcesat 2	LISS-IV	5.8	2014	NRSC
Resourcesat 2	LISS-IV	5.8	2015	NRSC
Resourcesat 2	LISS-IV	5.8	2016	NRSC

while the longshore transport rate $Q(x)$ is determined from tables relating the transport rate to the hydrodynamic conditions at breaking. Δx is user specified, while Δt is determined from stability criteria. From an initial coastline position $y_{int}(x)$ (x), the evolution in time is determined by solving the above equation, using an implicit Crank-Nicholson scheme.

3.4. Model set up

Initial coastline, bathymetry, wave climate and sediment characteristics are the major inputs required to run the LITLINE model. Bathymetry which is giving as a cross-shore profile and it starts from the offshore and extends up to two or three grid points in to the beach. The cross-shore profiles were generated from seven locations for estimating the shoreline evolution along the study region. The cross-shore profile locations VN3, VN2, VN1, VC, VS1, VS2, and VS3 are 0.6, 0.8, 1.2, 1.8, 2.8, 3.8 and 4.8 km south of northern boundary of the study region, respectively. The southern cross-shore profile (VS3) is much steeper (Fig. 3). The grid spacing of cross-shore profiles was 5 m and offshore depth is about 11 m.

Wave data collected during the 2015 for every 30 min interval at 15 m depth of Vengurla were used for computing shoreline evolution. Initial coastline was derived from satellite image for the year 2015. The Initial model run was for one year and calibrated with shoreline derived from the satellite image during 2016 (Noujas & Kankara, under publication). The model was further run for 26 years with this calibrated model. Sediment characteristics were given along with cross-shore profiles. The measured sediment characteristics from offshore and beach were given across the respective depth of the cross-shore profile position (grid) and interpolated for remaining cross-shore profile grids. The active depth (closure depth) is the basic calibration parameter in the LITLINE model.

4. Results & discussions

The major factors responsible for the coastal process along this sector are the geo-morphological settings of the coast and the hydrodynamics (Noujas et al., 2018). Geo-morphological settings include bathymetry, shoreline and beach topography. The major hydrodynamic parameters along this coast are wave, tide and coastal currents.

4.1. Long-term shoreline change

Long-term shoreline change rates for the past 26 years (1990–2016) were calculated at each transect by taking all the nine shoreline positions using WLR method. Overall shoreline change results suggest that accretion was the dominant class with highest accretion of about 1.6 m/yr observed at the southern side of the coast. Low erosion was seen further north about 1.6 km, north of present seawall. The northern side of the study area was in a stable condition. Overall, the long-term analysis shows that 3.4 km of coastal stretch fall under low accretion class. The entire study area has been classified into seven different classes (Fig. 4). A total of 42 m net shoreline movement was noticed on the southern side in the last 26 years. On the northern side, this net movement was 27 m. On the extreme north, it was −38 m. A net shoreline movement of −43 m was observed in the central region.

4.2. Short term shoreline change

Short-term shoreline change was carried out for four different period (2012–2013, 2013–2014, 2014–2015 and 2015–2016) using net shoreline movement method (NSM). The NSM determines the total distance between two shoreline positions. During 2012–2013, an accretion pattern dominated the entire coast, with a maximum horizontal distance of 23.5 m in the south of the study area (Fig. 5). However, in 2013–2014, an erosion pattern was observed along the coast, with a maximum net shoreline movement of −58 m along the southern side of the coast. Such reversal of the shoreline pattern was observed during two different periods. In 2014–2015, the erosion remained the same with a few meters of accretion at some patches of the coast. A second reversal was seen in 2015–2016, with erosion noticed only at the seawall region and 46 m beach advancement at the southern side of the study region.

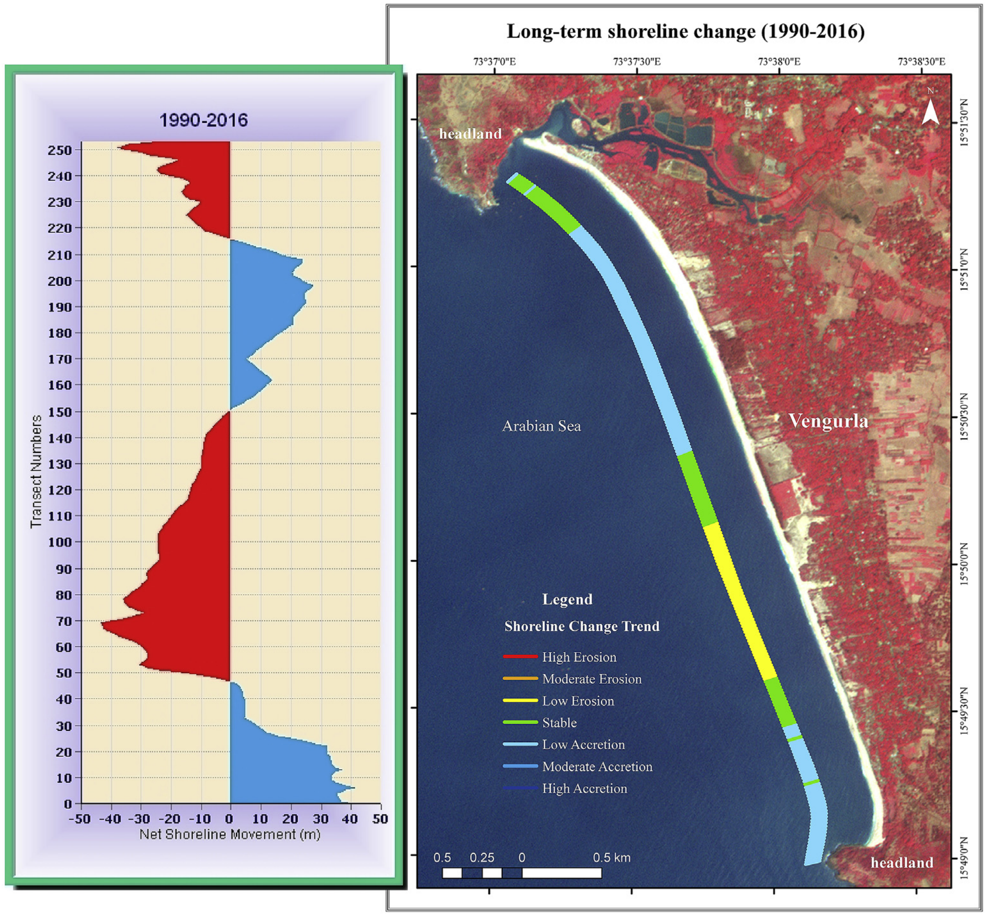

Fig. 4. Long-term shoreline change rate along study region (1990–2016).

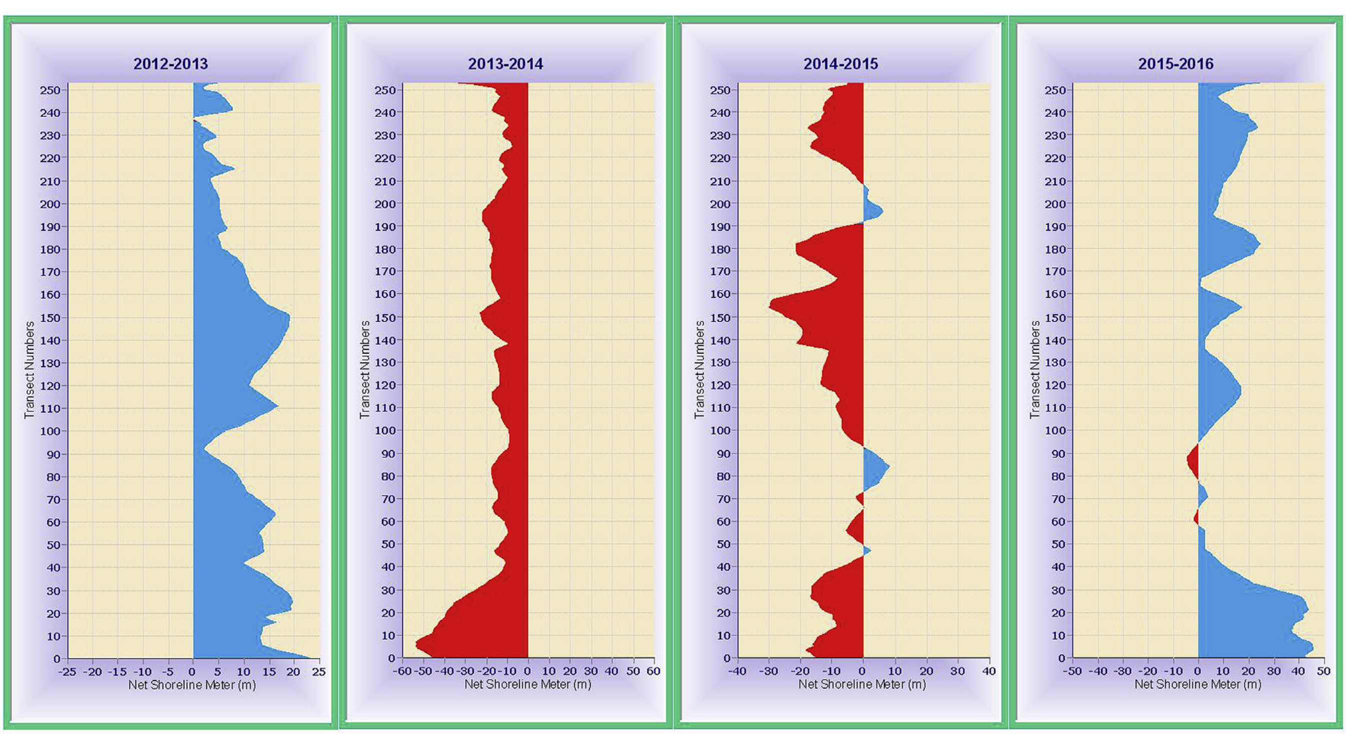

Fig. 5. Short-term shoreline change rate along study region.

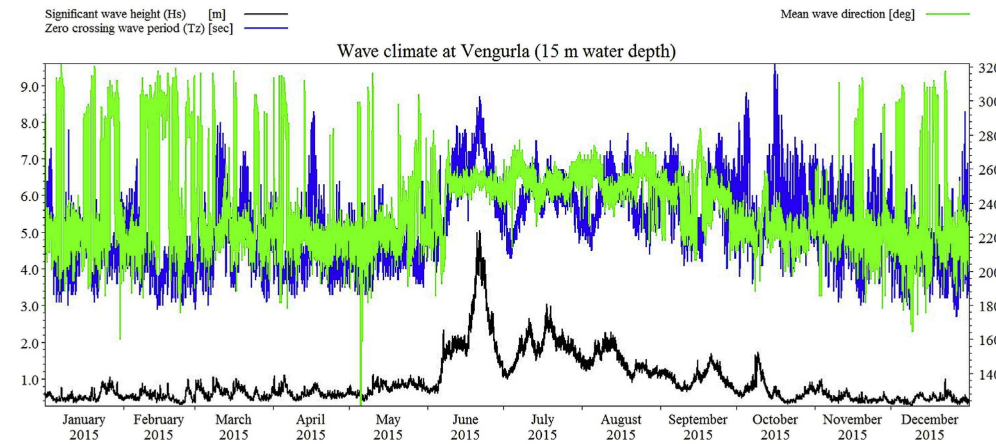

Fig. 6. Wave climate off Vengurla during the year 2015.

4.3. Coastal hydrodynamics

As mentioned above, wave data was collected at a depth of 15 m for one year in 2015. Significant wave height (H_s) was lesser than 1 m most of the time during the pre-monsoon season (February–May) and post-monsoon season (October–January) (Fig. 6). The zero crossing period (T_z) is in the range of 3–8. 3 s, and the mean wave direction is in the range of 121°–322° during the pre-monsoon season. Northerly waves during the pre-monsoon season may be due to shamal winds, and such winds were reported in Rathnagiri, approximately 150 km north of Vengurla (Aboobacker et al., 2011). H_s was higher and is in the range of 0.6–5.05 m during southwest monsoon (June–September) and highest H_s observed in the third week of June. The majority of waves were coming from west-south-west and west during the monsoon period. T_z has not much variation during monsoon and it is in the range of 3.9–8.7 s. The longest T_z was observed in October, reaching upto 9.6 s.

As the tidal range along the study region is between −1.2–1.2 m during the recorded period (ICMAM, 2017), it may not play any significant role in the coastal processes along this sector. The harmonic analysis was made using this data, noting that the tides are mixed semidiurnal in nature (Table 2).

Current speed ranged from of 0.29–22.3 cm/s during the recorded period at a depth of 7 m, with a mean of 7.8 cm/s. A Rose diagram for the period of observation shows that the predominant current direction is towards the south-east, and some currents are towards the north (Fig. 7). Coastal currents at a depth of 15 m were predominantly towards the south and southeast (Fig. 8). A maximum current speed of 23.75 cm/s and minimum of 0.29 cm/s were observed during this period at 15 water depth. The mean current speed was 9.32 cm/s, which corroborates the LSTR study conducted along the study region by Noujas et al. (2018). The LSTR is southerly during February, and northerly in March.

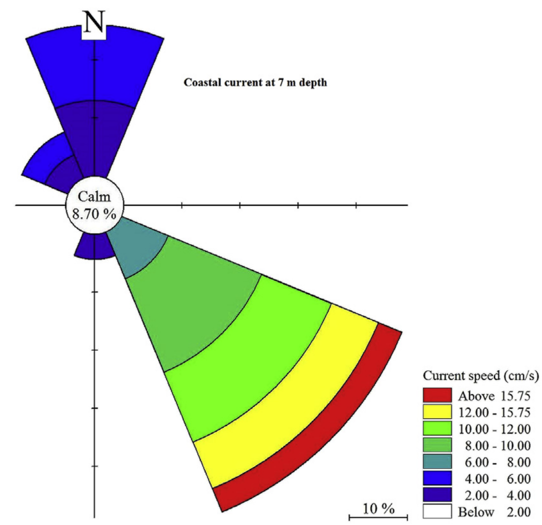

Fig. 7. Coastal Currents of Vengurla at a depth of 7 m.

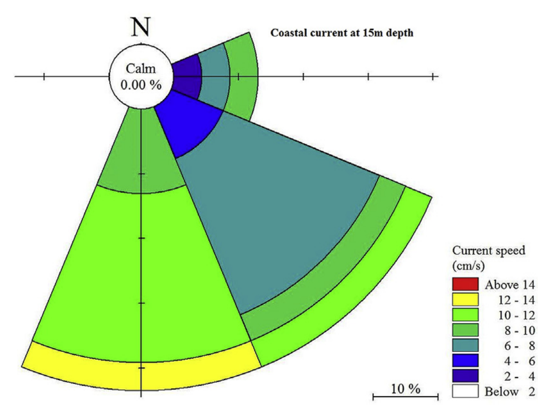

Fig. 8. Coastal Currents of Vengurla at a depth of 15 m.

5. Shoreline management plan

Coastal processes studies give an understanding of the extent of eroding coastal stretches that require management. Numerical modelling is a tool to understand future shoreline changes, and helps to suggest suitable shoreline management plans along the sector.

Numerical modelling was carried out for predicting the future shoreline change of the embayed beach of Vengurla by incorporating coastline, wave climate, cross-shore profiles and bathymetry as the main inputs for shoreline evolution. The initial coastline was digitized at every 10 m distance for a better representation of the coastline and was given as a distance from baseline. The baseline was drawn parallel

Table 2
Tidal constituents at Vengurla coastal waters.

Sl. No.	Tidal Const.	Amp. (m)	Phase (°)
1.	M2	0.55	309.56
2.	K1	0.76	71.47
3.	S2	0.26	355.86
4.	O1	0.64	53.49
5.	N2	0.11	290.55
6.	M4	0.01	11.54

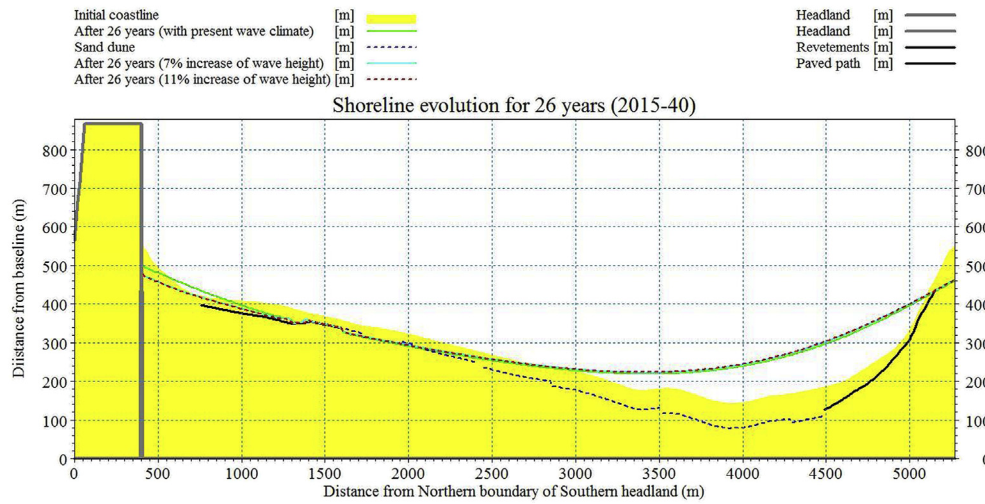

Fig. 9. Shoreline evolution for twenty six years along Vengurla (2015–40).

to the coastline. The coastline grid starts from the northern boundary of the southern headland and extends up to the northern boundary of the study region (0–527 Grids). The modelling was performed by including southern headland, revetment, paved path and sand dunes in respective places for better estimation of shoreline changes. Since there is no option to give headland in LITLINE structures, the southern headland was modelled as a combination of revetment and groin (0–40 Grids).

The 'LITCONV' utility of LITPACK was used to generate the wave climate in order to understand the shoreline evolution for the next 26 years. The results showed some erosion in the extreme southern sector of the study region, followed by accretion (~10 m) for 300 m alongshore distance (Fig. 9). Further north, the erosion rate increased (~30 m) before being followed by accretion. Accretion in the northern sector is about 3 m per year. In the extreme northern boundary of the study region, severe erosion was observed (Fig. 9), which may be due to the boundary problem in the model. Rajasree et al. (2016) used the same LITLNE model and extended the total length of the coastal stretch by some margin to avoid end errors. The shoreline changes for each year for the representative grids are given in Table 3. It is observed that the erosion in the southern sector reaches upto the present sand dune position after twenty years. If such erosion happens in the coming years, sand dunes need to be present and intact. Strengthening the dunes is the best long-term option for the protection of coast.

The model was further run with future climate scenarios, such as an increase of wave height by 7 and 11% (Black et al., 2017b). Sea level rise (SLR), which is expected to be of the order of 1 m globally (Stocker et al., 2013) or typically around 0.3 m over the next three decades and hence SLR was omitted in this study. The model result shows an erosion of 10–20 m in the southern sector, with only negligible change in the northern sector under the 7% increase of wave height scenario (Fig. 9).

The representative years and locations used to understand the quantitative change induced by the expected increases in wave height are given in Table 4. Erosion in the southern boundary is about 23 m in twenty six years, under the scenario of a 7% increase of wave height. There is only a marginal change of accretion in the northern sector (Table 4). There is no significant change in erosion/accretion pattern when wave height increases from 7% to 11% (Table 4).

At present, the Vengurla embayed beach is protected by various features including the headlands, artificial interventions in the form of both a seawall, and a paved path in the extreme south and north sectors of the beach (Fig. 2). In the southern sector, seawalls were constructed along the line of sand dunes in order to protect the houses. The model run predicted erosion that would reach upto the existing seawall and sand dunes after 20 years. However, in recent years, the sand dunes have been destroyed at some places for various reasons, including the construction of resorts, houses and other hard structures, as well as to make pathways for locals and beach visitors (Fig. 10). Black et al. (2017a) reported that the construction of houses and commercial buildings on primary dunes, although illegal under the CRZ regulations, are common along many beaches of Maharashtra. This leads to considerable costs for protecting the houses, as well as for the construction and maintenance of seawalls. In the southern sector, the sand dunes were also partially damaged due to storm events that occurred in past (Fig. 10d).

Based on model results, erosion may reach the sand dune position in the upcoming years. Any further damage to the sand dunes would further destroy the natural protection of the beach. The existing sand

Table 3
Shoreline rate at specific locations for 26 years (2015–2040).

Year/Grid[b]	41[c]	50	70	90	140	240[d]	340	440	490	510	527[e]
Initial[a]	554	496	430	412	377	280	177	177	282	423	550
2015	520	494	441	414	376	278	185	182	306	414	483
2016	513	491	446	416	374	277	186	186	315	410	464
2017	508	490	449	418	371	277	187	191	319	410	461
2018	506	489	451	420	369	276	188	196	322	411	461
2019	494	486	452	421	368	275	189	199	325	411	461
2020	492	485	452	422	366	274	190	203	329	412	461
2021	491	484	452	422	365	273	191	207	332	412	461
2022	485	483	452	422	364	272	193	211	335	413	461
2023	485	482	451	422	363	272	194	215	338	414	461
2024	485	481	451	422	362	271	195	219	341	414	461
2025	485	481	451	421	361	270	197	223	344	415	461
2026	485	480	450	421	360	269	198	228	346	415	461
2027	484	479	450	421	359	268	200	232	348	415	461
2028	485	479	449	420	359	268	201	236	351	416	461
2029	486	478	449	420	359	267	202	240	353	416	461
2030	487	478	448	419	357	266	204	244	355	417	461
2031	485	478	448	419	356	266	205	248	357	417	461
2032	488	478	447	418	355	265	207	252	359	417	461
2033	489	477	447	417	354	264	208	256	361	418	461
2034	490	476	445	416	354	264	210	260	363	418	461
2035	493	477	444	415	354	263	211	264	365	418	461
2036	491	477	444	414	354	263	213	268	366	418	461
2037	493	478	444	414	354	262	214	271	368	419	461
2038	496	480	444	413	354	262	216	276	370	419	461
2039	499	481	444	412	354	261	217	279	371	419	461
2040	498	482	445	412	354	260	219	282	374	420	461

[a] Distance from baseline in metre and it is applicable for all years.
[b] Grid spacing = 10 m.
[c] Extreme southern boundary.
[d] Middle sector.
[e] Extreme northern boundary.

Table 4
Shoreline rate at selected grids for 26 years in future climate scenario.

Year/Grid	50			90			340			510		
	Present	7%	11%	Present	7%	11%	Present	7%	11%	Present	7%	11%
2016	491	491	491	416	416	416	186	186	186	410	410	410
2025	481	469	471	421	418	419	197	198	198	415	415	415
2035	477	459	460	415	405	405	211	214	214	418	419	419
2040	482	459	458	412	400	400	219	222	223	420	423	423

Fig. 10. Sand dune destruction due to various reasons; a) Resort construction, b) House construction, c) For making pathway to locals, d) Due to storm event.

dunes have to be protected. Artificial sand dunes may be created where sand dunes are destroyed due to human intervention. Existing seawalls may get damaged when waves reach the seawalls after twenty years as predicted by the model. Seawalls getting exposed to waves and directly fronting the sea after twenty years may cause adverse impacts such as end erosion. Hence seawalls may be removed and artificial sand dunes may be developed to replace the seawalls. Dune vegetation may be planted and nurtured on both natural and artificial dunes for better coastal protection. Series of awareness programmes may be undertaken by the government for conservation of sand dunes for protecting this important embayed beach. Based on the present observation and modelling, it can be inferred that the shoreline of Vengurla will be affected not only by human intervention, but also by near future climate scenarios which include an increase of wave height. We propose that a dune-based shoreline management plan with strict regulations and awareness program is implemented. This would help to stop the destruction of sand dunes which provide a natural protection for this socio-economically important embayed beach along the west coast of India.

6. Conclusion

This study attempts to understand and estimate shoreline changes along Vengurla, an embayed beach along the west coast of India. Shoreline change analysis for preceding 26 years (1990–2016) showed 1.6 m/yr and 1.0 m/yr accretion in southern and northern sector respectively. The central and extreme northern sector of the study region showed an erosion of about 1.5 m/yr. Initially model run was carried out for one year and calibrated with shoreline derived from the satellite image. Then model was the run for the following 26 years (2015–40), with present wave climate and future expected increase in wave heights. The model predicts an average of 10 m beach advancement along the southern sector, 30 m erosion further north, and accretion of about 80 m in the northern sector of the study region in the next 26 years. Moreover, the erosion would reach the sand dune and existing seawall position after 20 years. Therefore, the destruction of sand dunes through illegal resort construction and other hard structure constructions including roads through dunes, would damage this naturally protected embayed beach in the near future. Moreover, the destruction of sand dunes that form a natural protection all along the coast would slowly affect the beach with long-term consequences. It may be concluded that the embayed beach of Vengurla is mainly affected by various anthropogenic modifications along this coast, which damage sand dunes. Future increase of wave height would only have a marginal impact. The development pressures that generate monetary income through the tourism economy of Vengurla need to be balanced by developing sustainable management strategies. We propose the implementation of a shoreline management plan with extensive dune care, strict regulations and awareness program.

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Appendix A. Supplementary data

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